EOS Validation of Aerosol and Water Vapor Profiles by Raman Lidar

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Abstract

We are developing methods to use the aerosol extinction and backscattering profiles measured by two separate Raman lidar systems to validate the aerosol climatology models used by two EOS AM sensors, MODIS and MISR. The aerosol retrieval algorithms used by these EOS sensors operate by comparing measured radiances with tabulated radiances which have been computed for specific aerosol models. These aerosol models are based almost entirely on surface and/or column averaged measurements and so may not accurately represent the ambient aerosol properties. Therefore, to validate these EOS algorithms, we are developing and plan to use the aerosol backscattering and extinction profiles measured by the CART Raman Lidar to determine how the aerosol properties over the SGP EOS Validation site vary with altitude and time. Additional activities focus on the use of the aerosol profiles measured by the GSFC Scanning Raman Lidar (SRL) during periodic field experiments to perform similar assessments.

We shall use the aerosol and water vapor measurements acquired by both systems for directly validating these EOS instruments. Ground-based measurements of the vertical profiles of atmospheric water vapor and aerosols are required both for direct validation of these instruments as well as to understand the physical processes which affect the retrieval of aerosols and water vapor from these satellite platforms. Both Raman lidar systems directly measure profiles of water vapor mixing ratio, aerosol

backscattering and extinction and can, therefore, also provide measurements of precipitable water vapor and aerosol optical thickness. We shall use the SRL aerosol data acquired during the TARFOX experiment at Wallops Island in July 1996 to assess the contribution made by different aerosol layers to the column integrated aerosol properties derived from the ground based sun/sky photometer measurements. We shall also use water vapor and aerosol measurements acquired by both lidars for similar studies during future experiments. Using the data from both lidar systems is a great asset for two reasons: 1) because it is a mobile instrument, the SRL will be able measure different types of aerosols at different locations, and 2) because it is designed for continuous, unattended operations, the SGP CART Raman lidar can acquire long term data sets required for validating EOS measurements over a long period of time.

Objectives

- Use SGP CART Raman Lidar measurements to investigate over an extended period the following effects on retrieval of aerosol properties from MISR, MODIS
    - —vertical variability of aerosol extinction, backscattering
    - —relative humidity effects on aerosol properties
    - —effects of clouds on aerosol properties
- Use GSFC Raman Lidar measurements to study the above effects for different aerosols during periodic campaigns:
    - —anthropogenic sulfates over eastern U.S.
    - —marine aerosols
- Use SGP CART Raman lidar measurements for atmospheric specification for CERES/CAGEX
    - —aerosol extinction
    - —water vapor mixing ratio
- Use Raman lidar aerosol extinction profiles to provide correlative data to validate SAGE-III aerosol extinction and water vapor profiles
- Use lidar measurements to validate MISR retrievals of cloud base, cloud top, cloud optical thickness

Background

Vertical profiles of both atmospheric water vapor and aerosols are required for evaluating EOS measurements, and perhaps more importantly, for understanding the physical and chemical processes which affect these retrievals of aerosols and water vapor from these satellite profiles. These measurements are needed to assess the effects of the vertical variability of aerosol optical and physical characteristics on the EOS MODIS and MISR retrieval algorithms. We are using profiles of aerosols and water vapor acquired by two separate Raman lidar systems to both evaluate these EOS measurements and to understand the processes which affect the retrievals from these EOS instruments.

The Atmospheric Radiation Measurement (ARM) (http://www.arm.gov/) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) Raman Lidar (http://www.arm.gov/docs/instruments/static/rl.html) and the NASA/Goddard Space Flight Center (GSFC) Scanning Raman Lidar SRL (http://rsd.gsfc.nasa.gov/912/Raman/raman.htm) both directly measure profiles of both aerosol backscattering and extinction and can, therefore, provide measurements of aerosol optical thickness to directly validate the EOS measurements. We are using the procedures developed for analyses of data acquired by the SRL to analyze the aerosol extinction and backscattering profiles measured by the SGP CART Raman Lidar. Because it is designed for continuous, unattended operations, the SGP CART Raman Lidar is well suited to provide the long term data sets required for validating the EOS MODIS and MISR measurements. Automated algorithms and software are currently being developed and should be implemented shortly to derive the aerosol scattering ratio and aerosol backscattering coefficient from this lidar system. Additional efforts are underway to develop and implement algorithms to directly compute aerosol extinction using the Raman nitrogen return signals. These algorithms are also based on those used for the analyses of data acquired by the GSFC Scanning Raman Lidar during periodic field experiments including:

TARFOX (Tropospheric Aerosol Radiative Forcing Observational Experiment) (http://prometheus.arc.nasa.gov/~tarfox/),

the First (http://www.arm.gov/~info/iops/wv_iop_wviop.html) and Second (http://www.arm/gov/docs/iops/1997/sep_integrated/index.html) Water Vapor Intensive Operations Periods, and

CAMEX-III (http://ghrc.msfc.nasa.gov/camex3/) (Convection and Moisture Experiment-III) to be held off the Florida coast in late-summer, 1998.

Technical Proposal

The technical proposal is given in the file EOS_validation.pdf which is an Adobe Acrobat file.

Lidar Systems

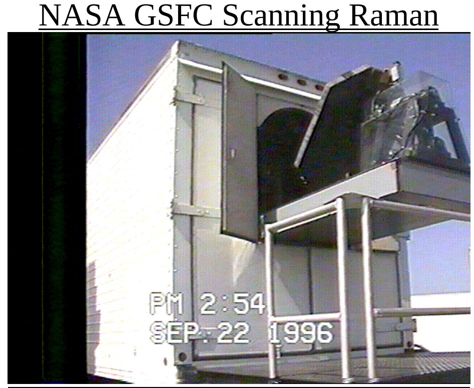
The CART Raman Lidar is an operational, autonomous system designed for unattended, continuous profiling of water vapor, aerosols, and clouds at the Department of Energy Southern Great Plains (SGP) site [1]. This system uses a tripled Nd:YAG laser, operating at 30 Hz with 400 millijoule pulses, to transmit light at 355 nm. A 61-cm diameter telescope collects the light backscattered by molecules and aerosols at the laser wavelength and the Raman scattered light from water vapor (408 nm) and nitrogen (387 nm) molecules. These signals are detected by photomultiplier tubes and recorded using photon counting with a vertical resolution of 39 meters. A beam expander reduces the laser beam divergence to 0.1 mrad, thereby permitting the use of a narrow (0.3 mrad) as well as a wide (2 mrad) field of view. The narrow field of view, coupled with the use of narrowband (~0.3-0.4 nm bandpass) filters, reduces the background skylight and, therefore, increases the maximum range of the aerosol and water vapor profiles measured during daytime operations.

The SRL operates in a similar manner but differs in that it is a mobile, trailer-based system designed for research conducted during intensive operation periods. Unlike the CART Raman lidar, which measures only vertical profiles, the SRL uses a steerable elliptical flat which provides full 180 degree scan capability within a single scan plane. This scan capability is used to increase the vertical resolution and precision of the data at lower altitudes as well as to facilitate comparisons with tower and/or surface-based instrumentation [2].

SGP CART

- Fixed Site
- Vertical Only
- Nearly Continuous Operation
- Nd:YAG (355 nm) Day/Night
- 61 cm diameter telescope
- Wavelengths
    - Rayleigh/Aerosol (355 nm)
    - Depolarization (355 nm)
    - Raman water vapor (408 nm)
    - Raman nitrogen (387 nm)
- 39 meter resolution
- low, high sensitivity channels

NASA GSFC Scanning Raman



- Mobil, Trailer Based
- Scans in one plane
- Periodic Measurements
- Nd:YAG (355 nm) day
- Excimer (351 nm) night
- Wavelengths
    - Rayleigh/Aerosol (355, 351 nm)
    - Raman oxygen (376, 372 nm)
    - Raman nitrogen (387, 383 nm)
    - Raman water vapor (408, 402 nm)
- 75 meter resolution
- low, high sensitivity channels

Data Products and Methodology

Aerosol

- Scattering ratio
- Backscatter coefficient
- Extinction Coefficient
- Extinction/Backscatter ratio
- Optical Thickness

Water Vapor

- Mixing Ratio
- Relative Humidity
- Precipitable Water Vapor

A summary of the primary products derived from the CART Raman Lidar, and their estimated uncertainties, is given in the following table.

Measurement	Altitude Range	Range Resolution	Temporal Resolution	Error	Precision	Detection Limit
Aerosol Backscattering (355 nm)	0.060-5 km	39 m	1 min	5% or 0.0003 km-sr^{-1} whichever is larger	2%	0.0002-0.0004 km-sr^{-1}
	5-15 km	156 m	10 min	5% or 0.0003 km-sr^{-1} whichever is larger	2%	0.0002-0.0004 km-sr^{-1}
	15-25 km (night)	312 m	10-30 min	5% or 0.0003 km-sr^{-1} whichever is larger	2%	0.0004 km-sr^{-1}
Aerosol Extinction (355 nm)	0.1-3 km	78 m (night) 156 m (day)	10 min	5% or 0.02 km^{-1} whichever is larger	5%	0.01-0.02 km^{-1}
	3-5 km	156 m (night) 312-624 m (day)	10 min	5% or 0.02 km^{-1} whichever is larger	5%	0.01-0.02 km^{-1}
	5-15 km	312-624 m (night)	10 min	5% or 0.02 km^{-1} whichever is larger	5%	0.02 km^{-1}
	15-25 km	312-624 m (night)	20-60 min	5% or 0.02 km^{-1} whichever is larger	5%	0.02 km^{-1}

Measurement	Altitude Range	Range Resolution	Temporal Resolution	Error	Precision	Detection Limit
Water Vapor Mixing Ratio	0.060-6 km	78 m (night)	1 min	5% or 0.002 g/kg whichever is larger	2%	0.002 g/kg
	6-8 km	78 m (night)	10 min	5% or 0.002 g/kg whichever is larger	2%	0.002 g/kg
	8-10 km	312 m (night)	60 min	5% or 0.002 g/kg whichever is larger	2%	0.002 g/kg
	10-12 km	312 m (night)	3 hour	10% or 0.005 g/kg whichever is larger	2%	0.005 g/kg
	0.138-3.5 km	78 m (day)	2 min	5% or 0.002 g/kg whichever is larger	5%	0.002 g/kg

A description of the data products from the Raman lidars is given below. Without loss of generality, all wavelength dependent products will be given for the CART Raman lidar, but similar products can be derived from the SRL Raman lidar's wavelengths.

<u>Aerosol</u>

- Scattering Ratio

The aerosol scattering ratio is one method to express the vertical distribution of aerosols. This parameter is defined as the ratio of the total (aerosol+molecular) scattering to molecular scattering and is expressed as $(\beta_m(\lambda,z)+ \beta_a(\lambda,z)) / \beta_m(\lambda,z)$ where β_a and β_m are the aerosol and molecular volume backscattering coefficients. The aerosol scattering ratio is derived from the ratio of the signal detected at the laser wavelength to the Raman nitrogen return signal. The combined aerosol+molecular backscattering is measured using the return signal at the laser wavelength (355 nm) while molecular backscattering is measured using the Raman nitrogen return at 387 nm. Provided skies are cloudfree, the lidar-derived aerosol scattering ratio is calibrated to unity at an altitude between 6-10 km since at these altitudes and wavelengths, aerosol scattering is negligible as compared to molecular scattering. Errors in the scattering ratio and backscattering cross section associated with this assumption should be at most a few percent. However, since the scattering ratio increases rapidly with wavelength, this assumption is not valid at longer wavelengths. Since periodic alignments and adjustments to the laser can affect this calibration, the aerosol scattering ratio calibration is checked and updated on a daily basis.

A correction is computed to account for the difference in atmospheric transmission between the return signal at the laser wavelength and the Raman nitrogen (or oxygen, in the case of the SRL) return signal. The difference in atmospheric transmission between the two wavelengths, which is due predominantly to the λ^{-4} wavelength dependence of molecular scattering, is derived by computing molecular scattering from the U.S. Standard Atmosphere profile. A correction is also applied to account for system dead-time and pulse pileup, which is the loss or gain of detected photons to incident photons due to each detector's characteristics.

Since the laser beam is not fully within the field of view of the telescope for ranges less than about 0.8 km, a correction is applied in computing the aerosol scattering ratio for altitudes below 0.8 km. This correction is derived by placing nitrogen interference (387 nm) filters in these two channels so that both channels observe return signals at the same wavelength. This nitrogen calibration function is then computed from the ratio of the return signals in these two channels. Since both channels observe the same wavelength, this ratio does not depend on the atmospheric state. Therefore, application of this nitrogen filter calibration permits retrievals of aerosol scattering ratio (and consequently aerosol backscattering cross section) profiles down to the lowest range gate acquired by the lidar, which is generally about 60 meters away from the lidar.

Both the aerosol scattering ratio and water vapor mixing ratio are computed using both narrow and wide field of channels. The aerosol scattering ratio from the wide field of view channels is used exclusively for altitudes below 1 km while the aerosol scattering ratio from the narrow channels is used exclusively for altitudes above 2 km; between 1 to 2 km the aerosol scattering ratios from the wide and narrow channels are linearly merged. The vertical resolution of these profiles varies with altitude to reduce the random error, decreasing from about 39 meters within the first few kilometers to a few hundred meters by an altitude of 9 km. This variation with altitude generally maintains the random error to below 10%. The maximum altitude of the aerosol scattering ratio and aerosol backscattering coefficient profiles depends on the vertical and temporal resolution. For the 10 minute averages, profiles extending throughout the troposphere can be obtained; increasing the averaging to 30 or 60 minutes permits the retrieval of stratospheric aerosol profiles during nighttime operations.

- Backscattering Coefficient

Profiles of the aerosol volume backscattering coefficient $\beta_a(\lambda=355 \text{ nm}, z)$ are computed using the aerosol scattering ratio profiles derived from the SGP Raman Lidar data and profiles of the molecular backscattering coefficient. The molecular backscattering coefficient is obtained from the molecular density profile which is computed using radiosonde profiles of pressure and temperature from the balloon-borne sounding system (BBSS) and/or the Atmospheric Emitted Radiance Interferometer (AERI). No additional data and/or assumptions are required.

- Extinction

These systems use the nitrogen Raman return signal to measure aerosol extinction. Aerosol extinction cross section profiles are computed from the derivative of the log of the Raman nitrogen signal with respect to range [3]. The outgoing wavelength is at 355 nm while the return Raman N_2 wavelength is at 387 nm so that the total aerosol extinction coefficient measured by the lidar is actually the sum of the aerosol extinction coefficients at 355 nm and at 387 nm. If the wavelength dependence of aerosol extinction is known, the aerosol extinction cross section can be found at either of these two wavelengths. The wavelength dependence λ^{-k} between 355 nm and 387 nm is normally assumed to be unity (k=1) but can vary depending on the size and composition of aerosols. Aerosol optical thicknesses measured between 340 nm and 440 nm by a Cimel sun photometer co-located with the SRL at the DOE SGP site near Lamont, OK during various experiments have shown k varies between 0 and 2. The error in the derived aerosol extinction at 355 nm using the Raman nitrogen signal is +/-10% if k varies between 0 and 2 when an assumed value of k=1 is used. However, in either case, the actual errors should be smaller for the retrieved profiles discussed here since the value of k normally used in the retrievals will be estimated using the wavelength dependence of aerosol optical thickness measured by the sun photometer. The discussion above assumes that the laser beam is fully within the field of view of the telescope so that the overlap function, O(r), is unity. For the SRL, this occurs for ranges beyond approximately 1 km so that, when the laser beam is directed vertically, measurements of aerosol extinction are computed for altitudes above 1 km. However, by scanning the lidar system so that data are acquired at low elevation angles, the aerosol extinction coefficient profiles are derived for altitudes as low as 100 meters. For the CART system, full overlap is achieved at approximately 800 m.

- Extinction/Backscatter Ratio

Profiles of the aerosol extinction/backscatter ratio are derived by dividing the aerosol extinction profiles by the aerosol backscattering profiles.

- Aerosol Optical Thickness

Aerosol optical thickness is derived by integrating the aerosol extinction profiles with altitude.

<u>Water Vapor</u>

- Mixing ratio

Profiles of water vapor mixing ratio are computed from the ratio of the Raman water vapor to Raman nitrogen return signals. Since the laser beam is not fully within the field of view of the telescope for ranges less than about 1 km, a correction is applied to this ratio to account for this overlap function. This correction is obtained by placing nitrogen filters in these two channels so that both channels observe return signals at the same wavelength. The overlap function is then computed from the ratio of the return signals measured in these channels. Since both channels observe the same wavelength, this ratio does not depend on the atmospheric state and is, therefore, used to measure the overlap function. Application of this nitrogen filter calibration permits retrievals of water vapor profiles down to the lowest range gate acquired by the lidar, which is generally 60 meters away from the lidar. A correction is also applied to account for system dead-time and pulse pileup, which is the loss or gain of detected photons to incident photons due to each detector's characteristics.

In addition to the overlap function correction, an additional correction is applied to account for the differential atmospheric transmission between the water vapor and nitrogen Raman wavelengths. This correction is mostly due to the wavelength dependence of Rayleigh scattering and increases with range away from the lidar, reaching approximately 7% at an altitude of 10 km. This correction is computed with sufficient accuracy using density profiles from standard atmospheric models, although density profiles computed from the coincident and collocated radiosondes could also be used. For hazy conditions, an additional correction must be applied to account for the differential attenuation due to aerosol scattering. This correction, which can reach as high as 3-4%, is computed from the aerosol extinction profiles measured simultaneously by the Raman lidar.

- Relative Humidity

Profiles of relative humidity are derived by combining the water vapor mixing ratio profiles described above with temperature profiles measured by either radiosondes, launched at the SGP site, or derived from radiances measured by the Atmospheric Emitted Radiance Interferometer (AERI).

- Precipitable Water Vapor

Precipitable water vapor is computed by integrating the water vapor mixing ratio profile with altitude.

Methodology

- Value-Added Procedure "RLPROF" – stage 1

There is presently a Value-Added Procedure (VAP) which creates profiles of water vapor mixing ratio, aerosol scattering ratio, and depolarization ratio from the signal return measured by the CART Raman Lidar. As there are narrow and wide field of views for this instrument (called the high and low channel, respectively, which is due to the altitude that each is more sensitive to), the water vapor mixing ratio and aerosol scattering ratio are computed for each channel. The low channel does not measure the depolarization of the elastic return, so the depolarization ratio can only be computed from the high channel data.

To create these data products, several steps are followed. This VAP first corrects each signal for system dead-time and pulse pileup (the loss or gain of detected photons to incident photons due to each detector's characteristics). It then ratios the appropriate channels and corrects the data for system overlap (geometry) affects. After accounting for the differential attenuation (the return signals at the different wavelengths attenuate differently), a calibration factor is applied to each profile. These calibration factors are determined outside of the VAP and are applied as constants. Finally, the derived data from the different channels are merged to form a single profile, and the data are output.

Some additional data quality fields are calculated and output with the primary data products (the ratios). These fields include indicators of the hatch condition (open or closed), a rough estimate of cloud base (a simple algorithm is currently being used), and maximum altitudes to use the ratio data (the altitude where the signal is lost in the background noise). These fields should be used in the analysis of the primary data products.

Details

The CART Raman lidar collects the raw data as 1-minute samples with a vertical resolution of 39 meters. Temporal and/or vertical averaging can be done to improve the signal-to-noise ratio. Currently, three temporal averages are done; 2-, 10-, and 30-minute products. For each, a temporal average interval, separate vertical resolutions for each derived product are possible. Therefore, the 2-minute water vapor mixing ratio may have a different vertical resolution than the 2-minute aerosol scattering ratio (ASR), which is different than the 10-minute ASR. Furthermore, the vertical resolution does not have to be constant with altitude; i.e., the resolution could be 78 meters for the first kilometer, increase to 39 meters for the next 4 kilometers, and then gradually decrease to 312 meters at 9 km.

After the resolution of the output is determined, the raw photons from all seven channels are read in and summed. The VAP then proceeds to correct the raw data for system dead-time and photon pileup. This correction assumes each detector (PMT and discriminator pair) is non-paralyzable, thereby specifying the correction equation [4]. Periodically, the instrument collects reduced strength profiles by inserting additional neutral density filters in all channels and attenuating the signal. Using both the normal full- and reduced-strength data together with the assumption of non-paralyzable, the correction is determined (by hand) and applied. The VAP proceeds to take the dead-time corrected data, subtract off the background component of each signal, and ratio the fields. After applying the differential attenuation correction to each ratio (this was calculated from the U.S. Standard Atmosphere), each profile is calibrated by multiplying the profile by a calibration constant that derived earlier. These ratios are the principal products of this VAP.

After the ratios are calculated, the data from the low and high channels are merged to form single profiles of water vapor mixing ratio and aerosol scattering ratio. These merged products are formed by linearly combining the two channels, where the weight is slowly shifted from the low channel to the high channel. For the water vapor mixing ratio, the merged product includes the mixing ratio derived from the point measurements on the SMOS, 25, and 60 meter towers, thereby extending this profile to the surface.

Several other fields are produced by this VAP as well, which should be used to ascertain the quality of the ratio products. The background levels of all of the channels are recorded in the netCDF file. Another field contains the output of a simple routine that attempts to determine the state of the hatch from the data (the opening/closing of the hatch is not directly recorded by the instrument), and is important since the instrument can still run with the hatch closed. The VAP also attempts to determine cloud boundaries, if a cloud exists, from the aerosol scattering ratio data. This is important as clouds can severely attenuate the signal. Finally, the altitude at which the signal strength approaches the background level is captured for each ratio, which serves as a practical limit on how high in altitude to use each ratio.

- Value-Added Procedure "RLAER" – stage 2

Another VAP, currently under development, continues the calculations of data products from the CART Raman lidar. First, the profiles of water vapor mixing ratio and aerosol scattering ratio (ASR) are automatically calibrated to remove any drifts in the calibration due to system affects (such as it automatic alignment adjustment). From the corrected ASR profile together with density measurements first from coincident radiosondes and in the future AERI retrievals, aerosol backscattering profiles are computed. The VAP then computes aerosol extinction from the nitrogen backscatter from the high and low channels, and then computes the aerosol extinction to backscatter ratio. Since the low channel overlap extends to approximately 800 meters, the extinction to backscatter ratio between 800 –1000 m is used to compute extinction from the backscatter profile down to the surface. From these various pieces, a merged extinction profile is created, which is then integrated to provide a measure of aerosol optical thickness. Profiles of relative humidity, calculated from the mixing ratio using the temperature profiles from radiosondes/AERI retrievals, and total precipitable water vapor are also included in this VAP's output. The final dataset includes the "best-estimates" of each of the following data products: profiles of water vapor mixing ratio, relative humidity, aerosol scattering ratio, aerosol extinction, aerosol backscatter, and the ratio of extinction to backscatter. Also included are total precipitable water vapor, aerosol optical thickness, and cloud base height.

Data Exchange/Archival

CART Raman Lidar

Water vapor and aerosol profiles retrieved from the CART Raman Lidar are archived on the ARM Archive. Water vapor mixing ratio, aerosol scattering ratio, and depolarization ratio profiles generated by the VAP RLPROF are contained in the output platform files called sgp2rlprofC1.c1 (2-minute averaged data), sgp10rlprofC1.c1 (10-minute averaged data), sgp30rlprofC1.c1 (30-minute averaged data). Under development is the software (RLAER) which will generate the similar output platforms called sgp2rlaerprofC1.c1 (2-minute averaged data), sgp10rlaerC1.c1 (10-minute averaged data), and sgp30rlprofC1.c1 (30-minute averaged data). The "best-estimate" data products will be contained in the files sgp2rlprofC1.c2, sgp10rlprofC1.c2, and sgp30rlprofC1.c2. These data can be easily accessed and downloaded from this Archive.

Other results derived from these investigations will be posted on this web page, and the MODIS and MISR teams will be notified of their availability. We also intend to present these results at the periodic MODIS and MISR Science Team meetings, ARM Science Team Meetings, as well as at other meetings.

Collaborations

We have been in contact with both the MODIS and MISR teams and have been recently named a MODIS Validation Affiliate. For MODIS validation, our discussions have focused on the use of the Raman lidar aerosol profiles to: 1) determine the altitudes of the aerosol layers that contribute to the aerosol optical thickness, 2) investigate the role of humidity in variations in aerosol optical thickness, and 3) how these interactions depend on the presence of clouds. We intend to use the estimates of aerosol size parameters obtained from both MODIS and MISR along with the aerosol optical properties measured by the lidar to infer additional optical and physical characteristics of the aerosols.

We have also been collaborating extensively with the DOE ARM community in the analyses of data from both lidar systems. Data acquired during the 1996 and 1997 Water Vapor IOPs by several different instruments (microwave radiometers, sun photometers, radiosondes, GPS, etc.) have been used to assess the water vapor measurements acquired by both lidars. In addition, we also have been collaborating with personnel from the Space Science and Engineering Center at the University of Wisconsin-Madison in combining temperature profiles, derived from radiances measured by the Atmospheric Emitted Radiance Interferometer (AERI), to derive profiles of relative humidity.

We also have been collaborating with the ARM Aerosol Working Group to determine how the Raman Lidar aerosol profiles can be used to characterize aerosol characteristics over the SGP site.

Results

Aerosol backscattering and extinction profiles have been computed for both the CART and NASA GSFC Raman lidar systems using data acquired during the 1996 and 1997 Water Vapor Intensive Operating Periods (IOPs).

Figure 1 shows an example of the aerosol backscattering and extinction profiles measured simultaneously by both lidar systems at 02:25 UT on September 23, 1996 during the 1996 Water Vapor IOP. Differences between the two lidars are generally within 5-10%. We are continuing to use the SRL aerosol data sets in assessing the aerosol extinction computed using the CART Raman lidar data.

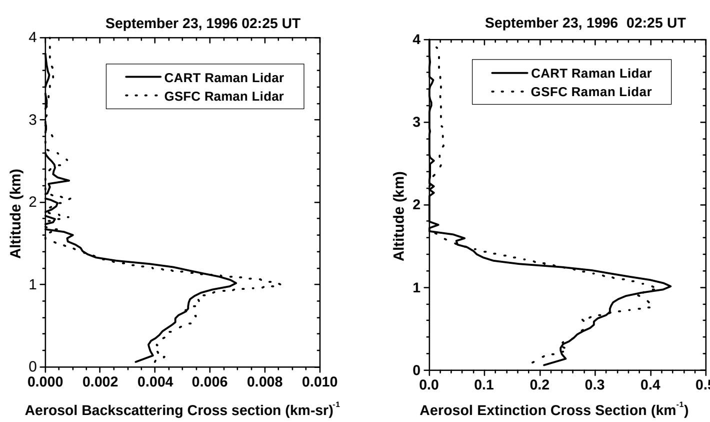


Figure 1. Aerosol backscattering (left) and extinction (right) profiles measured by CART and GSFC Raman Lidars at 02:25 UT on September 23, 1996.

During the 1997 Water Vapor IOP, the CART Raman lidar measured aerosol and water vapor profiles between September 25 through October 6. Images of the water vapor mixing ratio, relative humidity, and aerosol extinction profiles are shown in figure 2.

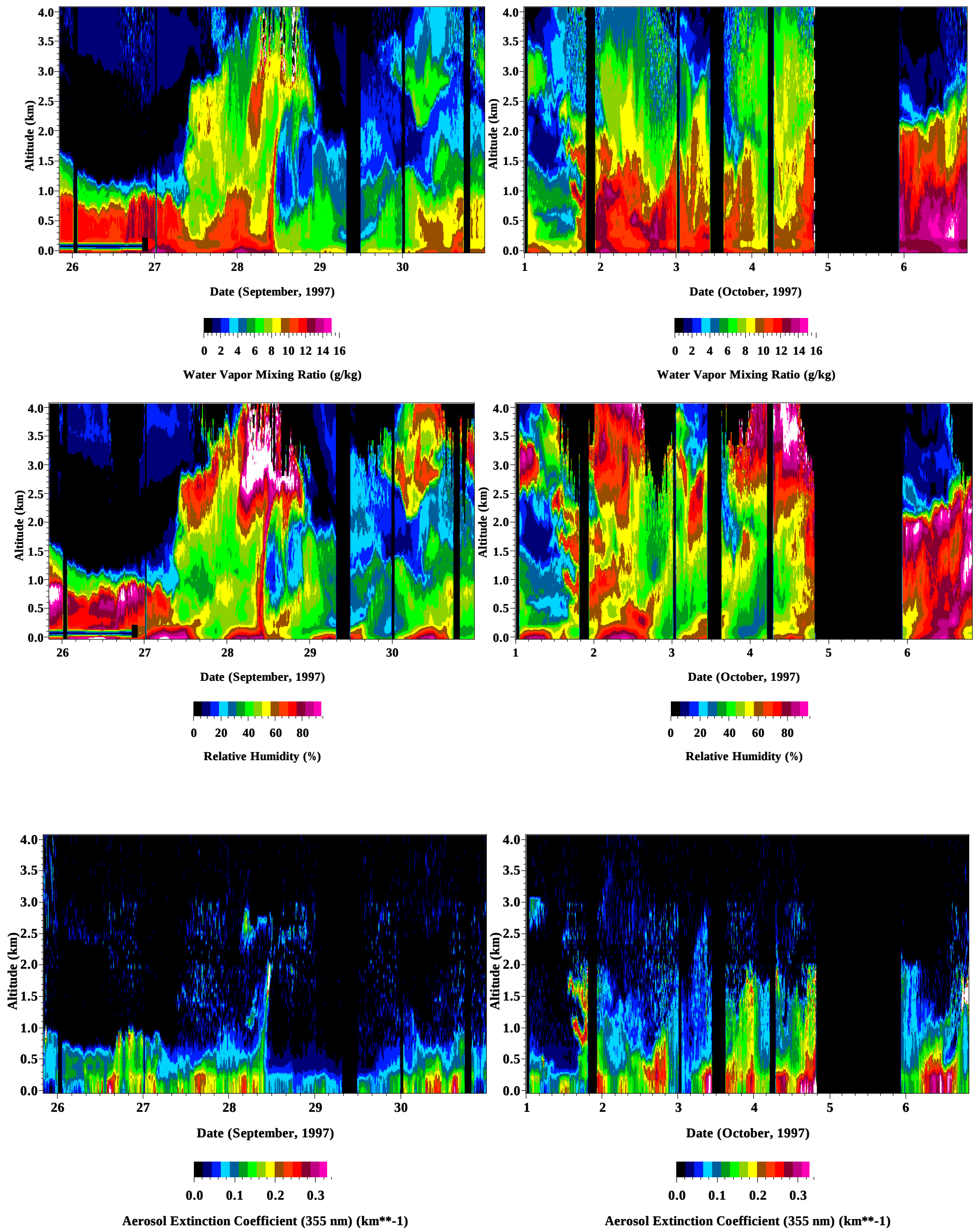


Figure 2. Water vapor mixing ratio (top), relative humidity (middle), and aerosol extinction (bottom) derived from CART Raman Lidar measurements during the 1997 Water Vapor and Aerosol IOP.

By integrating these aerosol extinction profiles, we have derived measurements of aerosol optical thickness and can compare these with coincident sun photometer measurements. The aerosol extinction profiles derived from the CART Raman Lidar data were integrated between 0 to 4 km to estimate the aerosol optical thickness. Figure 3 shows these values along with the aerosol optical thicknesses measured at 340 nm by a Cimel sun photometer located at the SGP site. The sun photometer measurements are restricted to cloud-free daytime periods. The excellent agreement between the aerosol optical thickness measurements from the two instruments is also shown in figure 4. The sun photometer aerosol optical thicknesses at 355 nm were determined by interpolating between the sun photometer measurements at 340 nm and 440 nm. The results indicate that, for this period, aerosols above 4 km have a negligible contribution to the total aerosol optical thickness. Figure 3 also shows that the precipitable water vapor derived from the simultaneous CART Raman lidar water vapor measurements is highly correlated with aerosol optical thickness. This indicates: 1) aerosol and water vapor concentrations within various air masses were highly correlated over the SGP site during this experiment, and 2) these aerosols tend to be hygroscopic so that the aerosol extinction increases with relative humidity.

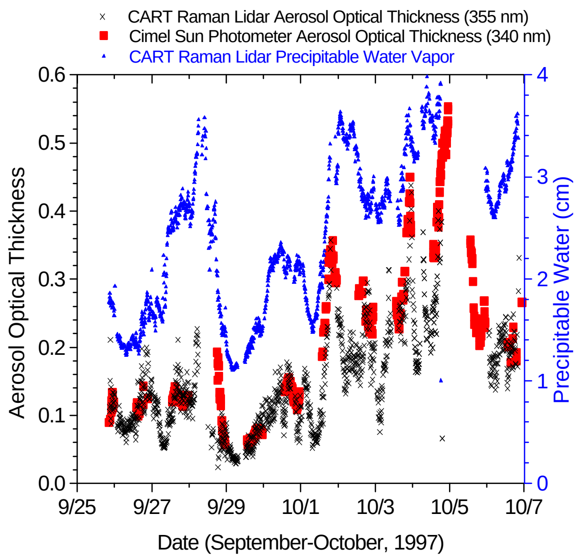


Figure 3. CART Raman Lidar and Cimel sun photometer aerosol optical thicknesses (left axis) and CART Raman Lidar precipitable water vapor (right axis) during the 1997 Water Vapor IOP.

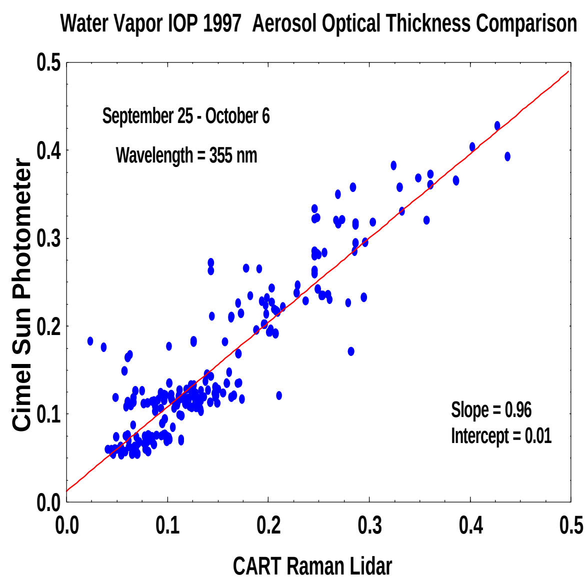


Figure 4. Correlation between CART Raman lidar and Cimel sun photometer aerosol optical thickness (355 nm) measurements during the 1997 Water Vapor IOP.

We have begun using the simultaneous water vapor measurements acquired by these Raman lidars to investigate the effects of water vapor on aerosol optical properties. For example, the relationship between aerosol extinction and relative humidity over the SGP site on October 6, 1997 is shown in figure 5. Aerosol extinction profiles measured by the CART Raman lidar and relative humidity profiles derived from the CART Raman lidar water vapor mixing ratio profiles and radiosonde temperature profiles are shown. Temporal resolution is 10 minutes while the vertical resolution is 39 meters. An increase in aerosol extinction and relative humidity below about 0.3 km, which occurred shortly after sunset at 00 UT, is followed by a decrease in aerosol extinction and relative humidity after sunrise at 12:30 UT. The increase in aerosol extinction with relative humidity between 01:00-09:00 UT is plotted in figure 6. Since the water vapor mixing ratio was approximately constant in this region during this period, this increase in relative humidity is due to the decrease in temperature associated with radiational cooling. Under these conditions, the increase in aerosol extinction is due to the change in aerosol physical characteristics (i.e. size and composition) rather than variations in the aerosol number concentration associated with varying air mass characteristics.

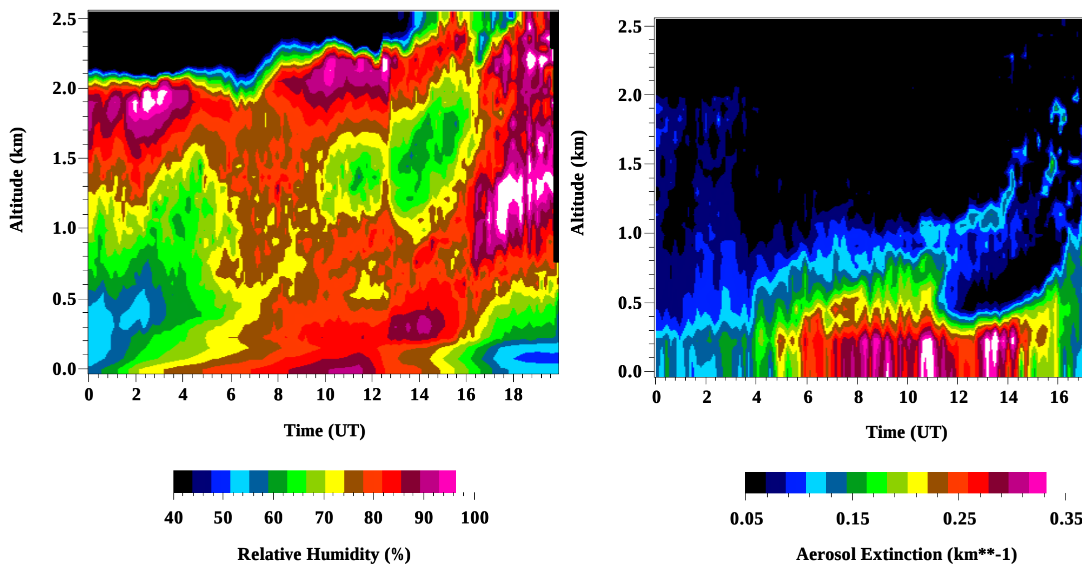


Figure 5. Relative humidity (left) and aerosol extinction (right) derived from CART Raman Lidar measurements acquired on October 6, 1997.

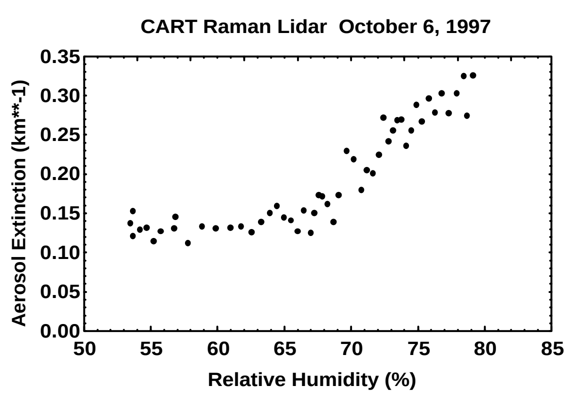


Figure 6. Aerosol extinction as a function of relative humidity derived for altitudes between 60-300 meters from CART Raman lidar measurements between 01:00-09:00 UT on October 6, 1997.

Status

CART Raman Lidar Instrument Status:

- During the Water Vapor and Aerosol IOPs at the SGP site in September-October 1997, the CART Raman Lidar acquired about two weeks of data after the laser was successfully repaired. The GSFC Scanning Raman Lidar acquired about three weeks of data during this same experiment.

- Following the 1997 Water Vapor and Aerosol IOPs at the SGP CF site, the CART Raman lidar was down for about two months pending acquisition and installation of new Multi-Channel Scalar data acquisition cards. System resumed operations in late January 1998 and continued until hard disk crash in March 1998. After computer repairs and upgrades were performed in March, CART Raman Lidar resumed operations in late March and has operated over 60% of the time, with no major problems.

The data acquisition status of the CART Raman Lidar is summarized in figure 7 which shows the percentage of time during each month this lidar system acquired data.

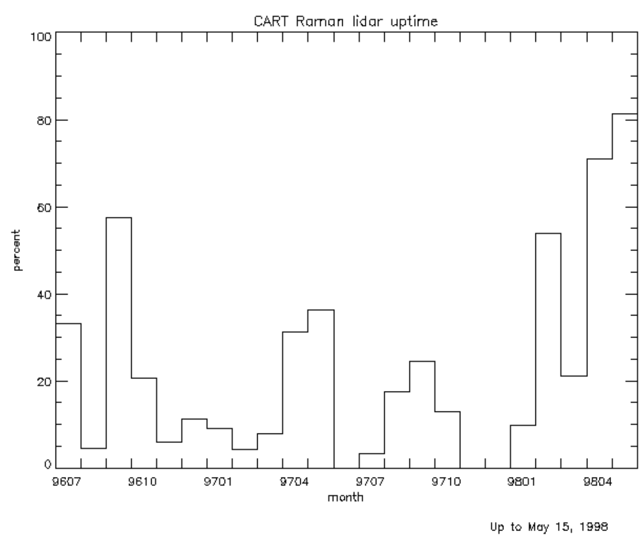


Figure 7. Percentage of run time for CART Raman Lidar during each month from July 1996 to May 1998.

CART Raman Lidar Data Processing Status:

Water Vapor

- Water vapor mixing ratio
  - algorithms and software developed and implemented as part of the RLPROF Value-Added Procedure (VAP)
  - "best estimate" product in RLAER (est. implementation date 8/1/98)
- Relative humidity
  - Algorithm and software which uses temperature from coincident radiosondes has been developed but not yet implemented into the Raman Lidar AERosol (RLAER) VAP (est. implementation date 8/1/98)
  - Algorithm which uses temperature derived from radiances measured by AERI and GOES is under development (est. development date = 7/1/98; est. implementation date = 8/1/98)
- Precipitable Water Vapor
  - Algorithm and software developed

Aerosol

- Aerosol scattering ratio
  - algorithm and software developed in RLPROF
  - "best estimate" product in RLAER (est. implementation date 8/1/98)
  - successful tested for WVIOP97 (Sept. 97) data
  - currently testing for data acquired throughout 1998
  - analyses of results obtained by automated routines to occur 9/1/98

- Aerosol backscattering coefficient
  - algorithm and software developed
  - successful tested for WVIOP97 (Sept. 97) data
  - currently testing for data acquired throughout 1998
  - automated routines should be in place by 8/1/98 (RLAER)
  - analyses of results obtained by automated routines to occur 9/1/98

- Aerosol extinction
  - algorithm and software developed
  - successfully tested for WVIOP97 (Sept. 97) data with comparisons to GSFC Scanning Raman Lidar
  - undergoing other comparisons with GSFC Raman lidar for WVIOP96 data
  - automated routines should be in place by 8/1/98 (RLAER)
  - analyses of results obtained by automated routines to occur 9/1/98

- Aerosol optical thickness
  - algorithm and software developed
  - successfully tested for WVIOP97 (Sept. 97) data with comparisons to Cimel sun photometer
  - undergoing other comparisons with GSFC Raman lidar for WVIOP96 data
  - automated routines should be in place by 8/1/98
  - analyses of results obtained by automated routines to occur 9/1/98

NASA GSFC Scanning Raman Lidar Instrument Status:

- Upgrade optical configuration to be completed by 6/1/98
  - Permits fiber optic coupling between telescope and detector
  - Facilitates new experiments
- Currently working on design of etalon-based measurement of aerosol extinction
- Will measure water vapor and aerosols at GSFC during June 1998 with coordinated measurements by Cimel sun photometer and MPL lidar to
  - Characterize “urban” summer aerosol profiles
  - Improve analysis routines for MPL retrieval of aerosol extinction
- Deployment to Andros Island in Bahamas in July 1998 for CAMEX-3 experimental operations during August-September. At CAMEX-3, will
  - Measure water vapor in sub-tropical environment
  - Continue coordinated aerosol measurements with Cimel sun photometer

NASA GSFC Scanning Raman Lidar Data Processing Status:

- TARFOX analyses complete; data archival to NASA Langley Research Center DAAC to be completed by 7/15/98
- 1996 Water Vapor IOP water vapor analyses complete; data to be archived to http://dev.ec.arm.gov/pub/wviop96 by 6/15/98
- 1996 Water Vapor IOP aerosol analyses in progress; data to be archived to http://dev.ec.arm.gov/pub/wviop96 by 8/15/98
- 1997 Water Vapor IOP water vapor analyses complete; data to be archived to http://dev.ec.arm.gov/pub/wviop97 by 6/15/98
- 1997 Water Vapor IOP aerosol analyses in progress; data to be archived to http://dev.ec.arm.gov/pub/wviop97 by 8/15/98

Publications

Ferrare, R.A., S.H. Melfi, D.N. Whiteman, K.D. Evans, R. Leifer, Y.J. Kaufman, Raman Lidar Measurements of Aerosol Extinction and Backscattering - Part 1: Methods and Comparisons, accepted by *J. Geophys. Res.*, 1998.

Ferrare, R.A., S.H. Melfi, D.N. Whiteman, K.D. Evans, M. Poellot, and Y.J. Kaufman, Raman Lidar Measurements of Aerosol Extinction and Backscattering -Part 2: Derivation of Aerosol Real Refractive Index, Single Scattering Albedo, and

Humidification Factor using Raman Lidar and Aircraft Size Distribution Measurements, accepted by *J. Geophys. Res.*, 1998.

Presentations

"EOS Validation of Aerosol and Water Vapor Profiles by Raman Lidar", R. Ferrare, S.H. Melfi, G. Schwemmer, D. Whiteman, K. Evans, D. Turner, Workshop for Atmospheric Validation in EOS-AM1 and SAGE III, Hampton, Virginia, October, 1997.

"Raman Lidar Measurements of Aerosol Profiles", Rich Ferrare, Dave Turner, S. Harvey Melfi, Geary Schwemmer, Dave Whiteman, Keith Evans, ARM Instantaneous Radiative Flux Working Group Meeting, College Park, Maryland, January 1998.

"CART and GSFC Raman Lidar Measurements of Atmospheric Aerosol Backscattering and Extinction Profiles for EOS Validation and ARM Radiation Studies", R. Ferrare, D.D. Turner, S.H. Melfi, D.N. Whiteman, G. Schwemmer, K. D. Evans, J.E.M. Goldsmith, T. Tooman, ARM Science Team Meeting, Tucson, Arizona, March 1998. (**http://www.arm.gov/docs/documents/technical/conf_9803/ferrare-98.pdf**)

"Comparison of measurements by the NASA/GSFC Scanning Raman lidar and the DOE/ARM CART Raman lidar", D.N. Whiteman, G. Schwemmer, D.Turner, K. Evans, B. Demoz, S.H. Melfi, M. Cadirola, S. Wise, R. Ferrare, J. Goldsmith and T. Tooman, ARM Science Team Meeting, Tucson, Arizona, March 1998. (**http://www.arm.gov/docs/documents/technical/conf_9803/whiteman-98.pdf**)

"Upper tropospheric water vapor: A campaign of two Raman lidars, airborne hygrometers, and radiosondes", S.H. Melfi, K. Evans, D. Turner, D. Whiteman, G. Schwemmer, and R. Ferrare, ARM Science Team Meeting, Tucson, Arizona, March 1998. (**http://www.arm.gov/docs/documents/technical/conf_9803/melfi-98.pdf**)

"Quantifying Mesoscale Flows in the Troposphere", B.B. Demoz, K.D. Evans, S.H. Melfi, M. Cadirola, D. O'C. Starr, D.N. Whiteman, G. Schwemmer, D.D. Turner, ARM Science Team Meeting, Tucson, Arizona, March 1998. (http://www.arm.gov/docs/documents/technical/conf_9803/demoz-98.pdf)

References

1. Goldsmith, J.E.M., F.H. Blair, and S.E. Bisson, Implementation of a Turn-Key Raman Lidar for Profiling Atmospheric Water Vapor and Aerosols at the US Southern Great Plains Climate Study Site, Advances in Atmospheric Remote Sensing with Lidar, A. Ansmann, R. Neuber, P. Rairoux, and U. Wandinger, eds. Springer-Verlag, Berlin, (1997) 337-340.

2. Ferrare, R.A., S.H. Melfi, D.N. Whiteman, K.D. Evans, F.J. Schmidlin and D.O'C. Starr, A Comparison of Water Vapor Measurements made by Raman Lidar and Radiosondes, *J. Atmos. Ocean Tech.*, **12**, (1995) 1177-1195.

3. Ansmann, A., M. Riebesell, and C. Weitkamp, 1990: Measurement of atmospheric aerosol extinction profiles with a Raman lidar, *Optics Letters,* **15**, (1990) 746-748.

4. Turner, D.D. and J.E.M. Goldsmith, 24-hour Raman lidar water vapor measurements from the Atmospheric Radiation Measurement Program's 1996 and 1997 intensive observation periods, submitted to *J. Atmos. Ocean Tech*., (1998).

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